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ABSTRACT

The constant demand for increased power and reduced mass has raised the internal temperature of conventionally cooled power magnetics toward the upper limit of acceptability. The conflicting demands of electrical isolation, mechanical integrity, and thermal conductivity preclude significant further advancements using conventional approaches. However, the size and mass of multikilowatt power processing systems may be further reduced by the incorporation of heat pipe cooling directly into the power magnetics. Additionally, by maintaining lower more constant temperatures, the life and reliability of the magnetic devices will be improved. A heat pipe cooled transformer and input filter have been developed for the 2.4 kW beam supply of a 30-cm ion thruster system. This development yielded a mass reduction of 40% (1.76 kg) and lower mean winding temperature (20° C lower). While these improvements are significant, preliminary designs predict even greater benefits to be realized at higher power. This paper presents the design details along with the results of thermal vacuum operation and the component performance in a 3 kW breadboard power processor.

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INTRODUCTION

Space power electronics has historically been presented with conflicting demands. Power requirements have increased from subkilowatt levels to the present low multikilowatt levels (<10 kW). At the same time advanced technology has allowed reduced component size and mass. Since an electrical device operating in a space environment is almost entirely cooled by conduction. With increasing power levels more waste heat must be removed. However the reduction in size limits the available surface area for thermal control. These competing constraints limit the power level of a conventionally designed power magnetic device.

A approach which increases the thermal conduction to the limited available area involves the insertion of a thermal conductor into the active (heat source) region of the transformer. Heat pipes are appropriate choices for such applications (Ref. 1). As the heat is transferred by the latent heat of the working fluid, relatively large amounts of heat may be transferred by small temperature differences. Additionally since in the liquid phase the heat pipe working fluid is "pumped back" by capillary action a heat pipe is particularly attractive for applications in zero gravity.

Adequate control of internal temperature, once achieved, allows the luxury of viewing a power magnetic device from a total system perspective. Significant system mass reductions may be realized by trading component power loss/mass against the corresponding power source and ultimate heat reduction system masses. While the optimum loss/mass trade off is mission specific, a value of 15 W/kg was selected for the particular designs being presented here. For the 2.3 kW transformer described in this paper this tradeoff allowed about a 0.6% reduction in efficiency for each kilogram of mass saved. Applying the same loss/mass approach to an input filter reactor involves an additional trade off of total inductance and capacitance mass. For purposes of this design exercise the same trade off value of 15 W/kg was selected.

TRANSFORMER DESIGN REQUIRMENTS

The heatpipe cooled power transformer was designed to be electrically interchangeable with an existing screen supply transformer used in a 30 cm ion thruster power processor (Refs. 2 and 3). This particular transformer was selected largely due to the advantage of demonstrating the transformer in a fully operational system. This approach not only provided the necessary experience, but also allowed a direct comparison against a conventionally designed transformer. The transformer is part of the series resonant inverter circuit shown in Fig. 1. When the power thyristor SCR1 is fired a sinusoidal current flows through the resonant tank (LA, CA, and CB) and the power transformer T. On the alternate half cycle, thyristor SCR2 is fired and current flows in the reverse direction through the resonant tank and transformer T.

To avoid complications in the system testing program imposed by a gravity orientation requirement for the transformer heatpipes, all "all attitude" requirement was imposed upon the design.

To satisfy the "all attitude" requirement two stainless steel/methanol heatpipes were used in each transformer coil, each capable of handling the total thermal dissipation. The heat pipes were straight cylinders placed back to back. This placement provided two operational pipes in space or in a horizontal attitude on earth. However if placed in the worst possible attitude on earth at least one operational heatpipe per coil would maintain the temperature rise within safe limits.

Transformer Configuration

The electrical design of the transformer required the inclusion of an electrostatic shield between the primary and secondary windings (Fig. 2). The shield was additionally utilized in this design as a heat collecting surface for the heatpipes. This insured that the heat pipe would be operating at zero electric potential. The two coil single core design provided maximum surface for heat transfer from the resulting single layer primary winding. Other advantages of this configuration include reduction of the mean length of turn, reduced leakage reactance, and a shorter thermal path to the base plate.

The configuration of a single transformer coil is shown in Fig. 3. Two salient points concerning the heat pipes should be observed: the evaporator has been flattened to minimize nonconcentricity of the windings, and the condenser section has been enlarged to provide adequate surface area within the mounting space available.

Thermal Analysis

A computerized thermal analysis was performed based upon the electrical design and the predicted thermal characteristics. Using this technique various configurations could be evaluated without costly hardware itterations and associated testing. The thermal analysis predictions for the final configuration were found to correlate quite well with the actual operating temperatures observed during thermal vacuum testing (Fig. 4).

The correlation between the computer predictions and actual test data was not only gratifying, but also created confidence in the ability to produce much higher powered magnetics having predictable thermal characteristics. Figure 5 shows the heat pipe cooled transformer together with the original screen supply transformer. As a final observation, if the application would allow equal hot spot temperatures in both transformers, the heatpipe cooled design is actually capable of handling power in excess of 3.5 kW.

Input Filter Inductor

As the input filter inductor represents the second heaviest magnetic device in the power processor it was also selected for weight reduction through improved cooling. The first stage input filter comprised of LI, C, and R (Fig. 6) controls the resonant peaking of the filter. The peak current demands of the power processor are satisfied by the second stage comprised of L_2 and C_2. The design of this filter stage is optimized for minimum total weight consistent with the electrical requirements a decrease in the specific mass (kg/mH) of the inductor. Therefore would be attended by a corresponding reduction in total capacitor mass. For this application a 2.6 mH inductor weighing 840 grams, was redesigned as a 5.8 mH inductor weighing 500 grams. To satisfy the all attitude requirement for the input filter inductor, an unique "double ended" heat pipe was developed. This particular heat pipe has a single continuous tube with a single evaporator section and two condenser sections. In this design the heat pipe is attached directly to a copper coil form allowing maximum thermal transfer

Figure 7 shows a comparison between two first stage input filters, one is the heat pipe cooled inductor, and the other the conventionally designed inductor it replaces full details of the design and fabrication of the transformer, the inductor and their associated heatpipes are contained in the final contractors report (Ref. 4).

Testing

In order to verify the electrical equivalence and the thermal integrity, the transformer and inductor were tested under thermal vacuum conditions. An operational 2.3 kilowatt bread board power processor served as a testbed. The test consisted of a full power operation with a 50° C heat sink, a series of 12 in operating thermal cycles. Each thermal cycle consisted of a 90 minutes at 100° C, 90 minutes at -50° C, with 90 minutes allowed for transition between these extremes. The 90 minute periods selected were in excess of six transformer thermal time constants, and are adequate for full temperature stabilization. A thermal profile comprising both internal and external temperatures, and the corona inception voltages of the windings, were obtained both before and after the thermal cycling. A device exhibiting and variation in these parameters during this rather extreme test has demonstrated the physical integrity necessary for long term reliability.

CONCLUSIONS

A heat pipe cooled version of the high frequency (20 kHz) high power (3 kVA) high voltage (1.52 kV) transformer reduced the already low specific weight of the conventional conduction cooled design from 0.57 kg/kW to 0.4 kg/kW. The worst case temperature rise was reduced from 40° to 20° C even though the internal loss was increased from 30 to 40 watts (a tradeoff figure of 18.6 W/kg).

A 3.7 kW, 20 A input filter inductor was also redesigned with heat pipe cooling integrated into the coils enabling a 40% weight reduction in the inductor, a 50% weight reduction in the filter and a low 10° C internal heat rise. A thermal vacuum test verified the tradeoff of 16 W/kg.

Testing in a thermal vacuum chamber using the actual operating power circuit breadboard tgo excite the magnetics verified the internal heat flow and temperature rise predicted by the analytical thermal modeling program.

The close correlation between the predicted temperatures and the final operating temperatures creates confidence in computer modeling as a design tool. Use of the computer model will allow analysis of proposed designs without costly fabrication of several itterations. This will be particularly advantages in the design of higher powered magnetic devices.

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3. Biess, J. J., Inouye, L. Y., and Schoenfeld, A. D., "Electric Prototype Power Processor for a 30-cm Ion Thruster," TRW Defense and Space Systems Group, Redondo Beach, Calif., TRW-28014-6001-TU-00, Mar. 1977. (NASA CR-135287)

4. Chester, M. S., "Heat Pipe Cooled Power Magnetics," TRW Defense and Space Systems Group, Redondo Beach, Calif., NASA Contract NAS3-21372, Final Report (NASA CR-159659)

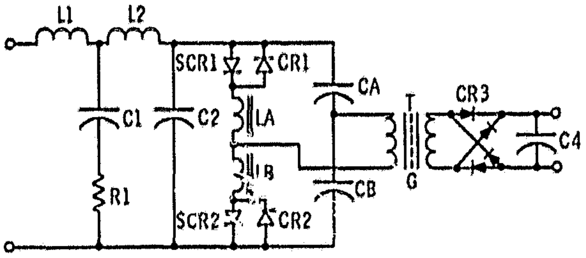
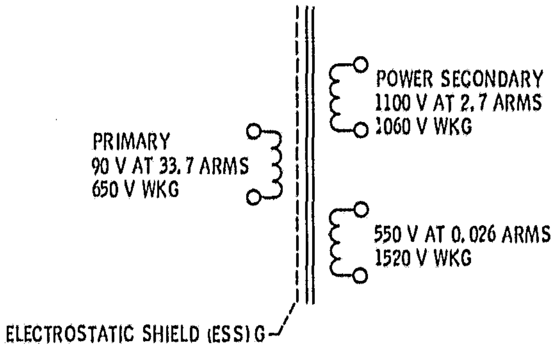


Figure 1. - Series resonant inverter with auxiliary diode configuration.



PRIMARY SOURCE:
SQUARE WAVE VOLTAGE, APPROXIMATE SINE
WAVE CURRENT, 20 kHz MAX
REPETITION RATE VARIABLE WITH INPUT VOLTAGE & COMB.
TEMP:
0 TO 50° C BASEPLATE OPERATE, -55 TO 100° C NONOPERATE
MAX AVG WINDING RISE 35° C WHEN FULLY LOADED MOUNTED ON
50° C BASEPLATE
EFF:
APPROXIMATELY 99 percent TRADED OFF AGAINST WEIGHT

Figure 2. - Screen supply power transformer requirements.

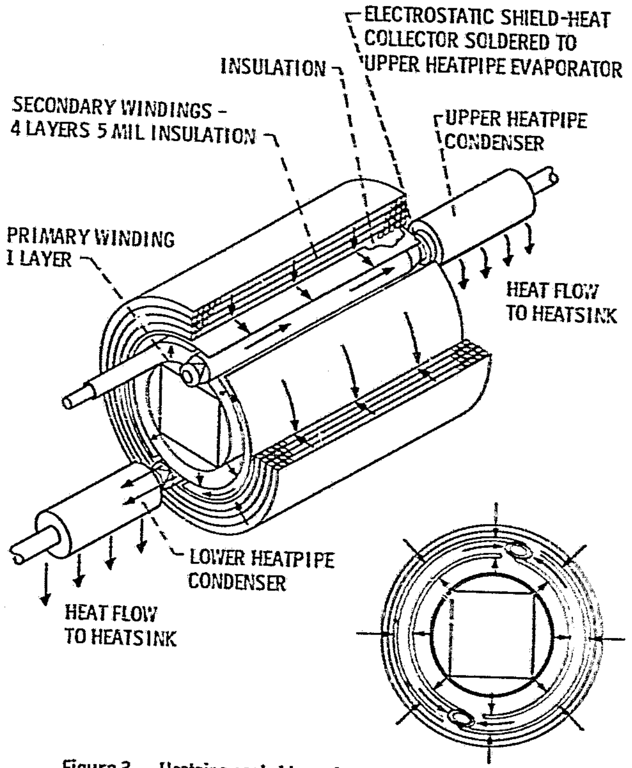
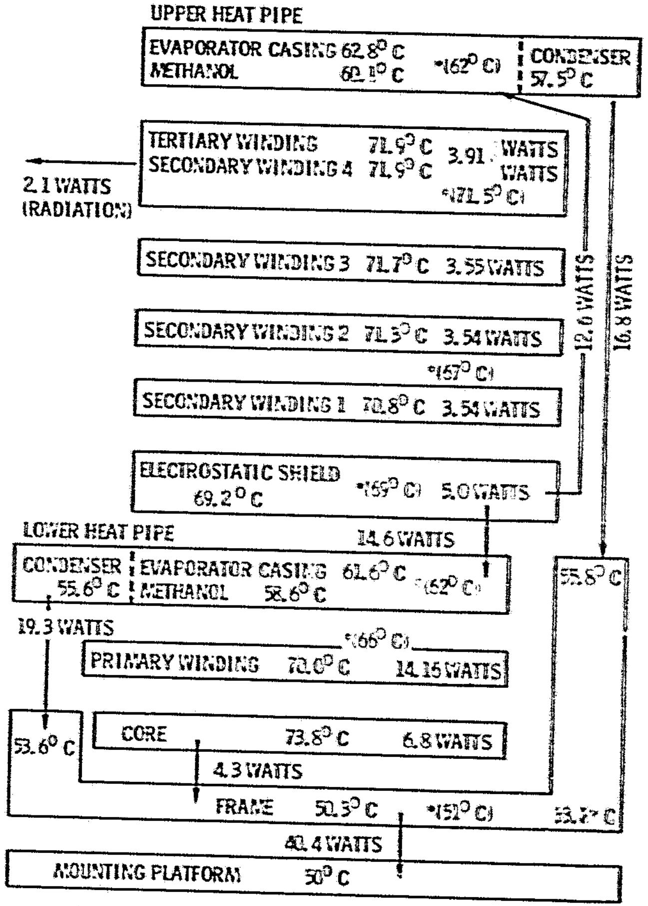


Figure 3. - Heatpipe cooled transformer heat flow paths.



*TEMPERATURES OBSERVED DURING VACUUM OPERATION

Figure 4. - Correlation of predicted and measured temperatures.

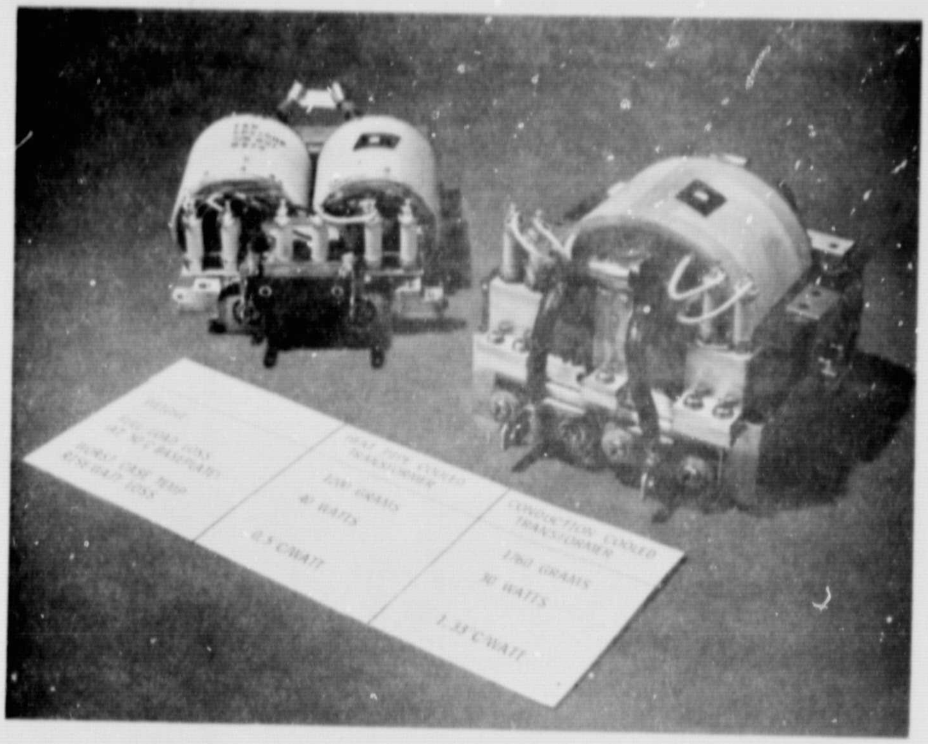


Figure 5. - Transformer mass comparison.

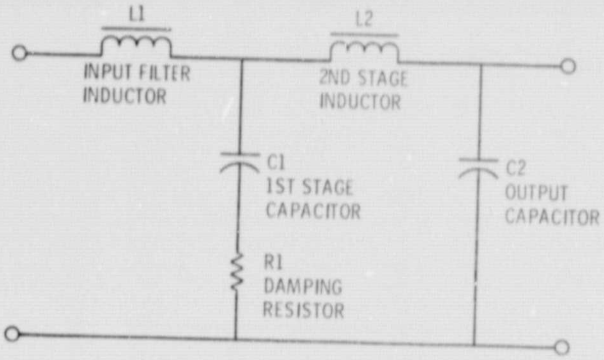
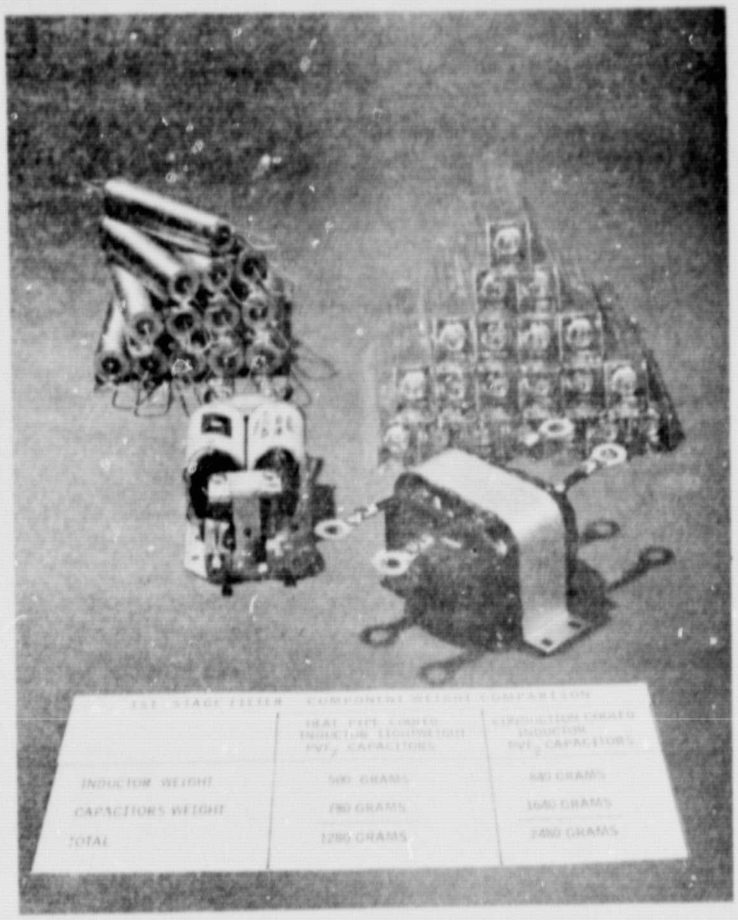


Figure 6. - Basic two stage input filter.



1ST STAGE FILTER COMPONENT WEIGHT COMPARISON

	HEAT PIPE COOLED INDUCTOR LIGHTWEIGHT PVF$_2$ CAPACITORS	CONDUCTION COOLED INDUCTOR PVF$_2$ CAPACITORS
INDUCTOR WEIGHT	500 GRAMS	840 GRAMS
CAPACITORS WEIGHT	780 GRAMS	1640 GRAMS
TOTAL	1280 GRAMS	2480 GRAMS

Figure 7. - First stage filter component weight comparison.